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Deep Space 1 Flight Experience: Adventures on an Ion Drive

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DEEP SPACE 1 FLIGHT EXPERIENCE: ADVENTURES ON AN ION DRIVE

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NASA/JPL's Deep Space 1 was launched in September of 1998 as a low-cost mission to flight-test solar electric propulsion, autonomous navigation and several other high-risk technologies that enable future planetary projects. This paper provides a brief overview of the DS1 attitude control subsystem, shares a few lessons-learned, and describes some of the many daunting challenges faced by our tiny flight team during the course of the mission. Special focus will be given to the nuances of flying a spacecraft with ion propulsion, our nick-of-time re-write of the attitude determination software after the failure of the on-board star tracker in late 1999, and DS1's subsequent successful flyby of comet Borrelly on September 22, 2001.

INTRODUCTION

Deep Space 1, the first mission of NASA's New Millennium Program, was launched September 24, 1998 on flight to test 12 high-risk technologies with promise to benefit future planetary projects. The project was among the lowest cost planetary missions NASA has ever flown. The entire DS1 project was executed for only $160M, including launch vehicle, mission operations, and extended-mission costs. DS1's technology payloads include a high performance Ion Propulsion System (IPS) powered by a 2.6 KW advanced solar concentrator array, an autonomous navigation system (AUTONAV) capable of planning and correcting a low thrust trajectory to a small-body encounter, and two low-mass, high-capability science instruments, MICAS and PEPE. The unique nature of the project and the single-string design of the DS1 spacecraft would present many challenges to the flight team during the mission.

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ACS CONFIGURATION

The DS1 Attitude Control System (ACS) includes (Figure 1) a Lockheed AST Stellar Reference Unit (SRU) to provide inertial attitude, a Litton LN200 Inertial Measurement Unit (IMU) to sense spacecraft body rates, and an eight thruster monoprop Reaction Control Subsystem (RCS). A two-axis Adcole digital Sun Sensor Assembly (SSA) is used as a cross-check on the SRU and for attitude reference in safe-hold. Each of the spacecraft's two solar panels is mounted via a 1-axis Solar Array Drive Assembly (SADA) providing 360 deg articulation. The solar panels are constructed with pop-up cylindrical concentrator lenses. As a result, the SADA gimbals must be positioned within about 2 degrees of the optimal orientation if the array is to provide power. DS1's distinctive ion engine is mounted to the spacecraft via a 2-axis gimbal with +- 5 deg range of motion in each axis.

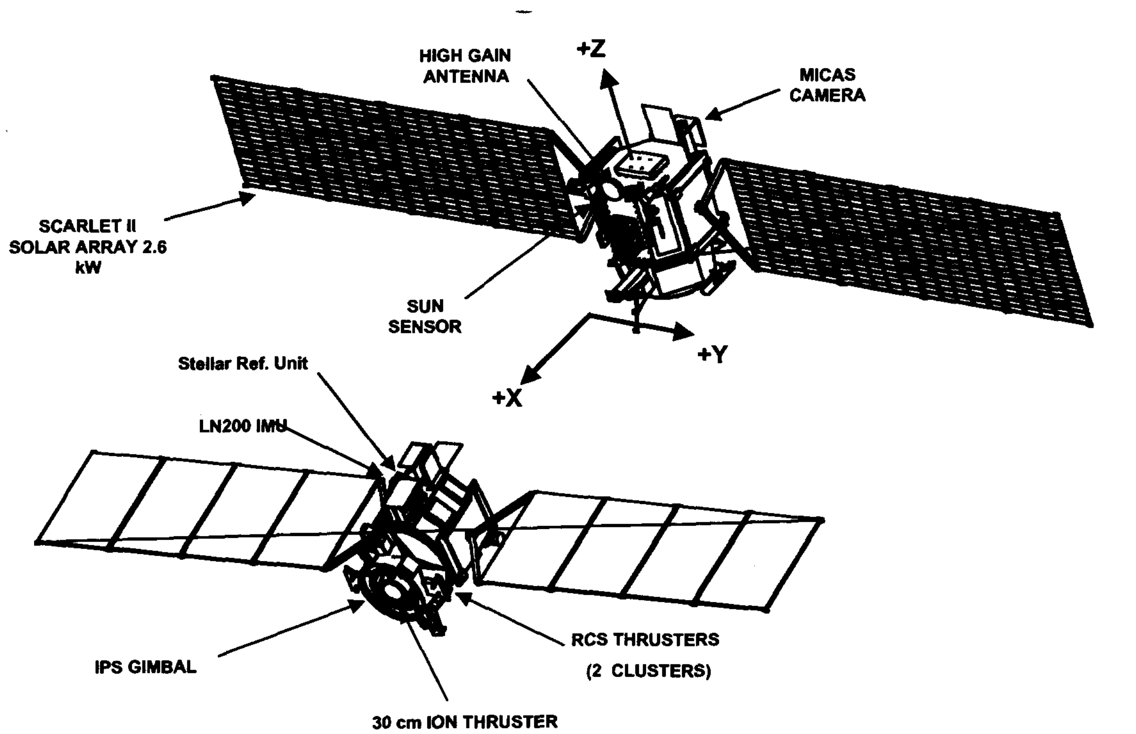


Figure 1 **DS1 ACS Configuration**

ION PROPULSION EXPERIENCE

The Ion Propulsion System (IPS) used on DS1 consists of a xenon propellant feed system (XFS), a power processing unit (PPU) and a single ion thruster. A digital control computer (DCIU), interfaced to the spacecraft through a MIL-STD 1553 data bus, regulates the propellant feed rates, the voltages and currents required to start and operate the thruster. In the thruster, atoms of Xenon propellant are singly ionized in a discharge chamber and then accelerated electrostatically between a pair of molybdenum grids (Figure 2). The effective exhaust velocity is around 40 km/sec. The IPS can be throttled between 20 and 90 mN, at power consumption of 500 and 2500 Watts respectively. Achievable Isp ranges from 2000 to 3100 sec depending on thrust level. In flight, the IPS proved remarkable robust, operating for a total of 16000 hours (640 days!) without an unplanned shutdown, failure to start, or other serious problem.

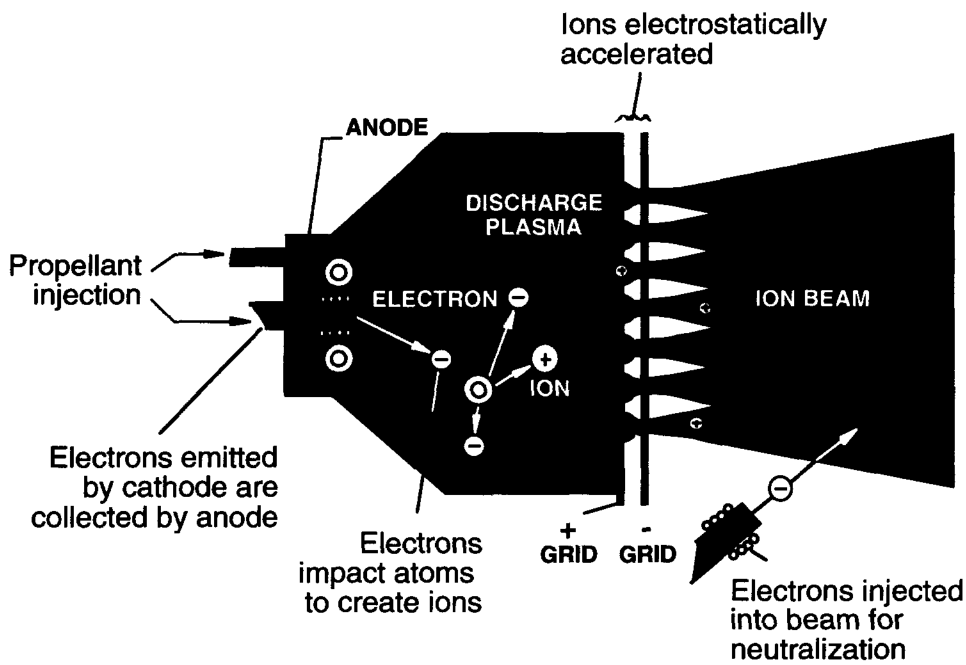


Figure 2 **IPS Thruster Schematic**

Thrust Vector Control

The DS1 ion engine is mounted in a stepper motor driven gimbal to correct for random and grid-wear induced variations in the thrust vector. Thruster gimbaling also allows the ion engine thrust to be used to control the attitude about the spacecraft X and Y axes. This control mode, called Thrust Vector Control (TVC), greatly reduces the consumption of hydrazine when the IPS is in operation. In TVC mode, all three axes of the conventional bang-bang RCS control loop continue to operate, but the ion engine generated torques keep the X and Y axes within the RCS deadbands so the corresponding thrusters do not fire.

Because TVC mode is able to make tiny changes in torque by moving the IPS gimbal, very small control errors and rates about the X and Y axes can be achieved (Figure 3). The improved pointing stability in TVC was exploited on DS1 to allow much longer exposures with the (Z-axis aligned) MICAS camera than were possible under RCS thruster control alone. The improved sensitivity of optical navigation pictures (~1.5 magnitudes) achievable using this technique should continue to be exploited in future missions using IPS.

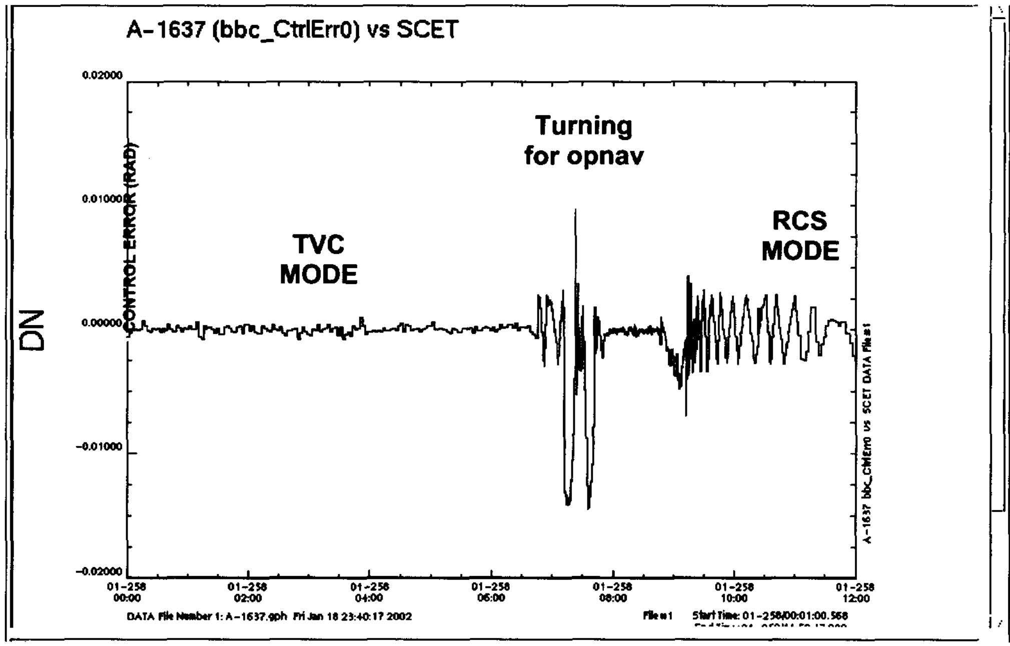


Figure 3 **Comparison of TVC and RCS Control Errors**

Whether in RCS or TVC mode, the spacecraft Z-axis was always controlled via the RCS thrusters. Late in the mission, in an effort to reduce hydrazine consumption, the Z-axis deadbands were made as large as +- 2 degrees. This revealed that one-sided deadbanding was occurring when the IPS was in operation. We have estimated that at end-of-mission a secular Z-axis torque of about 1e-5 Nm was being applied to the spacecraft by the ion engine. Future projects using IPS should be careful to account for such effects in their budget for RCS propellant.

One of the engineering challenges of the DS1 ion engine implementation was the transition from RCS to TVC. During the switch, spacecraft rates must be reduced from the nominal RCS deadbanding values to a level within the control authority of the TVC control loop. In the DS1 design, this was a software-automated process that included several changes to the RCS deadbands and a delay period to allow estimation of the null-torque gimbal position. Flight experience left us surprised at the amount of RCS propellant consumed in the process. Future missions should take care to budget propellant for this activity and ensure that sufficient IPS gimbal travel and slew rate is available to allow for prop-efficient transitions.

Other IPS "lessons learned" relate to the IPS gimbal hardware itself. The DS1 design uses potentiometers to sense the position of the IPS gimbal. These data are used for telemetry and by software that prevents the gimbal from being commanded against the hard stops. During the flight, the pots became increasingly noisy and unreliable, forcing us to disable the gimbal-stop protection. Since the TVC control loop commands the IPS gimbal only via relative commands, it was not affected.

IPS gimbal position readout is a challenging application for potentiometers because of the high temperatures near the ion thruster and the repeated wear near the center of travel. Future missions should strongly consider the use of a non-contact position sensor such as an LVDT or optical encoder for this application. The actuators driving the IPS gimbal also experience the majority of their wear near the center of their travel ranges, and lifetime specifications need to be written accordingly.

Finally, the DS1 TVC control loop as designed seemed overly sensitive to rate noise from the IMU. This resulted in near continuous small motions of the IPS gimbal actuators, considerably increasing their wear and mean power consumption. Adjustments to the tuning of the TVC controller could likely reduce or eliminate the problem. Since power margin can often translate directly into achievable thrust level and missed-thrust margin, future projects using IPS should give particular attention to the system engineering issues related to the TVC control loop.

THE PRIMARY MISSION

DS1 was designed and built on a highly aggressive schedule. Only slightly over 3 years elapsed from project conception to launch. Flight operations followed at an equally rapid tempo. Technology validation tests began within days of launch and continued without respite throughout the primary mission. It was common for the flight team to support three or more complex, first-time activities each week, developing and testing the required command sequences in under two weeks.

Between (and often during) these tests DS1 experienced a multitude of in-flight "surprises". In the first four weeks of flight, there were five significant ACS related anomalies, including and SEU induced solar array offset, an uncommanded thruster event and a power distribution unit anomaly that caused the SRU to drop briefly offline. Fortunately, the frequency and severity of unexpected events seemed to decrease with time.

The primary mission culminated in a close flyby of asteroid Braille in July of 1999. By September of that year, DS1 had achieved all of its mission success criteria, operated the IPS for 3000 hours, and completed 10 recoveries from safe-hold, the last, a mere six hours before the flyby.

FLYING BLIND

In November of 1999, two months after the end of the successful primary mission, DS1's single-string SRU failed (Figure 4). Onboard fault protection software unsuccessfully attempted to clear the fault by power-cycling the unit and later commanded yet another entry into DS1'S safe-hold mode, SUNSSA. On entry to SUNSSA, the spacecraft selects a low gain antenna, aligns both solar array normals with the boresight of the High Gain Antenna (HGA) and points the arrays to the Sun. SUNSSA was designed as a minimum-hardware configuration, and uses only the sun sensor, IMU and RCS thrusters for control.

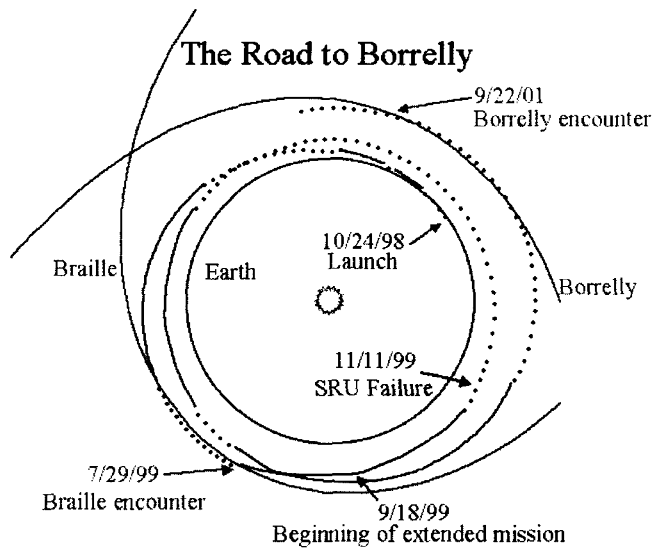


Figure 4 The DS1 Trajectory

Over the next several weeks, challenged by the reduced data rate, we worked to understand the failure and develop options for continuing the mission. Without the SRU, the spacecraft had no way to determine inertial attitude. This left us unable to perform turns, point the HGA to Earth for high data rate communications, or to thrust with the ion engine and maintain the planned trajectory. Diagnosis and recovery efforts included additional power cycles of the unit, turning on additional SRU telemetry channels, and the activation of SRU internal diagnostic modes.

By February of 2000, we had concluded that the SRU had suffered a serious internal short and was not recoverable. It had also become clear that the ability to thrust with the ion engine could not be in time to stay on the planned trajectory to comets Wilson-Harrington and Borrelly.

Consulting at length with the science and engineering teams and our NASA sponsors, the project developed an extremely challenging recovery plan. By removing the Wilson-Harrington encounter from the flight plan and re-optimizing the trajectory for a Borrelly-only mission, it was possible to delay the start of IPS thrusting until mid summer. This would give the team slightly over four months to devise and implement a system to determine attitude and restore our ability to thrust. Significant changes to the ACS flight software would have to be made, but before a new software build could be uploaded, high rate communications via the HGA would have to be restored.

Earth Pointing: The Hard Way

To enable high rate software uplink and facilitate further investigation of the SRU anomaly, the flight team devised a method to point the HGA to Earth. This rough-and-ready procedure came to be known as "Earth Coning". In SUNSSA the high gain antenna is controlled to the sunline using only the 0.5 deg resolution sun sensor and IMU. Fortunately, the designers of the SUNSSA software had included a very flexible capability to point the spacecraft including offset pointing and turns about the sunline. These "bonus" features allowed us to point a carefully chosen body-offset-vector to the sun and then roll about the sunline at a commandable rate.

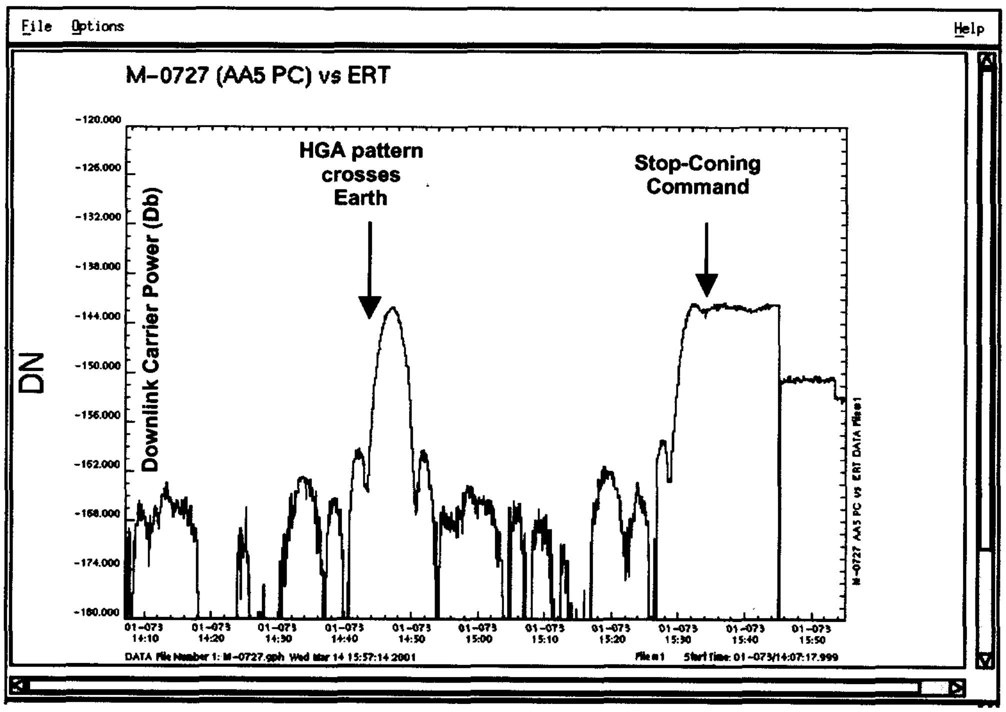
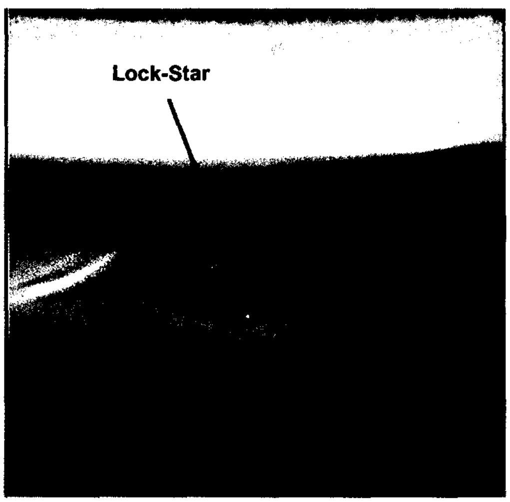


Figure 5 **Downlink Power During "Earth Coning"**

With proper attention to the geometry, the HGA pattern could be made to sweep across the Earth on each spacecraft revolution. After observing the periodic variations in downlink signal power for several revs, a precisely timed command was sent to stop the rotation with the HGA pointed to Earth (Figure 5). As gyro bias errors caused the spacecraft to drift slowly around the sunline, additional commands were occasionally sent, turning the HGA back to the optimal position. After a bit of practice, these improvised techniques allowed High Gain Antenna communications to be established and then maintained for much of each telemetry pass. HGA communications were thus reestablished on Jan 14, 2000.

Development of the MURKY Software

During the 4 short months between February and May of 2000, a small team of ACS and NAV engineers conceived, designed and implemented the new attitude determination software. The system, whimsically named MURKY, finds the spacecraft inertial attitude using star images taken with the MICAS science camera and data from the sun sensor. In operation, the MURKY software makes an exposure about twice per minute. The image is passed to the AUTONAV software where a modified version of the onboard optical navigation image processing code is used to find star centroid and magnitude information. To help reduce stray light artifacts that corrupt MICAS camera images at many attitudes (Figure 6), each MURKY star picture is subtracted from a suitable "background" image and cropped before centroiding. The centroid data are used as input to a star identification module where image-to-image correlation takes place.



SRU

- 8.8 X 8.8 deg FOV
- Mag 7.5 sensitivity
- 0.25 sec update period
- Provides full attitude quaternion

MICAS Science Camera

- 0.8 X 0.5 deg usable FOV
- Mag 6.5 sensitivity
- 30 sec update period
- Provides image file to MURKY software
- Requires sun sensor data to compute full 3-axis attitude

Figure 6 A Raw MICAS Star Image

Because of the MICAS camera sensitivity limit (about mag. 6.5) and its small field of view (< 1 deg square), attitudes that allow multi-star images are comparatively rare. As a result, MURKY was designed to use only the single "best match" centroid from each image. A vector measurement residual is computed between the predicted and observed positions of this single "lock star" in each image. To allow the estimator to find the rotation about the lock-star, the software also computes measurement residuals from the 0.5 deg resolution Sun sensor data. These two new types of attitude measurements required the existing Kalman filter based attitude estimator software to be extensively modified. A 2 degree-of-freedom "vector measurement" data-type was added and used for both star and sun sensor data.

An executive module within MURKY controls the exposure of star pictures and handles the acquisition and loss of the lock-star. During acquisition, MURKY waits for control errors and rates to fall below a threshold and then begins shooting paired images a few seconds apart. MURKY uses the star centroid data to update the attitude only if matched centroids appear in both images. After certain confidence criteria are met, MURKY switches to a tracking mode where attitude updates are made from single image frames. If, for any reason, MURKY loses lock on the star, it continues to process frames for a short time before returning to acquisition mode. If the lock-star still cannot be found, the MURKY executive begins searching for it, commanding a programmable sequence of small mosaic turns.

Because the deadline to begin thrusting would allow only a single opportunity to upload the software and many elements of the design would have to be optimized on the fly, new parameters were added liberally. Implementation of the MURKY software required the addition of 65 new commands and over 100 parameters. In several cases, features were coded into the software based on no more than a hunch they might be useful, leaving them disabled until the hour of need. Rather than risk modification the existing spacecraft command handling routines, the new MURKY commands were implemented by a clever extension to the existing ACS parameter table.

Learning to Fly Again

For DS1 to keep its September 2001 appointment with comet Borrelly, thrusting had to resume by July 2000. In order to give the maximum possible time for the crash-development of the MURKY code, the software uplink was scheduled to complete on June 8, 2000. This left only four weeks to improvise a set of procedures to operate the new software, make any critical parameter changes and get the entire MURKY system working reliably on the spacecraft.

Exploiting an image synthesis capability built into the AUTONAV software, the DS1 Testbed was modified to allow full system-level closed-loop testing of the MURKY code. Using this "new and improved" Testbed, the complex set of sequences and procedures for activating MURKY were developed and tested over a period of a few days while the new flight software was being uplinked to the spacecraft. With the deadline fast approaching, the activation of the MURKY software was a do-or-die proposition. At each step of the process, the flight team was called upon to make dozens of critical parameter and procedural choices, often based on little more than engineering intuition.

To the flight team's relief (and considerable surprise) the many "educated guesses" made over these hectic weeks paid off. After improvising our way through the attitude initialization process, MURKY found it's first lock-star on June 12. Nine days later, we started the ion engine and began thrusting to reach Borrelly.

Having successfully resumed powered flight, our operational approach became conservative literally over night. Uncertain of how robust the MURKY system might be, we kept parameter and procedural innovation to the absolute minimum. As time passed and MURKY continued to function, confidence in the software slowly grew. While spacecraft operations using MURKY was certainly labor intensive, the system proved to be remarkably robust, locking to many dozens of stars and flawlessly carrying the spacecraft through 4 weeks of solar conjunction. MURKY lost star lock only four times during the rest of the mission, twice because of image processing idiosyncrasies, and twice due to image corruption apparently caused by showers of solar protons.

PREPARING TO ENCOUNTER COMET BORRELLY

As the week-to-week activities fell into a routine, the flight team's attention turned to the Borrelly encounter. With the failure of the SRU, design of a successful comet encounter became an extremely challenging endeavor. Of most immediate concern was the propellant situation. Thanks to the deletion of the Wilson-Harrington flyby, ample xenon remained for the ion engine. Unfortunately the long period in SUNSSA and the repeated use of "Earth coning" had left only an estimated 9 kg of hydrazine. Even optimistic estimates of the prop consumption rate indicated this was insufficient. The crux of the problem was a 6-month period of "coast" demanded by the trajectory. In coast, without the gimbaled ion engine running to reduce RCS thruster activity, propellant was being used too quickly.

The solution to the dilemma came to be called "impulse-power". The strategy was to reduce the throttle level to the lowest controllable value and thrust for a week or so at time roughly toward the north or south celestial pole. This saved RCS propellant by running the ion engine, while reducing the impact on the trajectory as much as possible by canceling the effect of the ion thrust.

Even counting the hydrazine savings afforded by impulse-power, the propellant budget remained extremely tight. The prediction for worst-case consumption still showed the tanks running dry before reaching Borrelly. In response, several steps were taken to further reduce prop consumption including increasing the Z axis deadbands, reducing the number of optical navigation periods prior to the flyby, and making modifications to MURKY parameters to limit the number of mosaic turns. The biggest savings ultimately came from the NAV team, whose orbit determination accuracy and clever terminal targeting strategy eliminated the need for trajectory corrections using the RCS. As a result, the Borrelly flyby was targeted to within a few km of the intended aimpoint using only ion propulsion.

Other ACS concerns as we approached Borrelly included the debris environment near the comet and IMU performance. Analysis of the debris flux predicted by current comet models showed that a direct attitude upset cause by particle impact was unlikely, but indicated there was substantial risk of impacts having enough energy to damage components of the unshielded spacecraft. The high ratio of particle energy to momentum is the direct result of the high (16.5 km/sec) flyby velocity. Since moving the flyby to a "safe" range would have severely reduced the science data return, the project elected to accept the debris impact risk.

Because of the large uncertainties in the optical characteristics of the comet nucleus, it was decided not to use the MURKY software to lock to Borrelly itself. Instead, we selected two MURKY lock-stars close to the line of sight at different phases of the encounter. The spacecraft would use these for attitude fixes, turning to track and image the nucleus on integrated IMU data alone. Using two stars helped to maintain pointing accuracy as the line of sight to the comet changed in the hour before flyby. .

Since IMU performance was key to the success of the encounter, it was a major area of attention. A study to determine angle random walk and gyro bias stability was undertaken using flight data. While performance appeared to be sufficient, large uncertainty in the gyro noise model parameters remained. As at the Braille encounter, the AUTONAV software was used throughout the flyby, processing images of the target, estimating the encounter time and geometry, and making appropriate corrections to the science camera pointing. To give ourselves confidence the encounter would work, we performed well over a hundred testbed and Monte-Carlo simulations of the flyby.

Figure 7 The Nucleus of Comet Borrelly

CONCLUSION

On September 22, 2001, the Deep Space 1 spacecraft passed within 2200 km of comet Borrelly. High-resolution images of the nucleus have provided scientists with a detailed look at the topography and morphology of the comet's surface. Stereoscopic coverage of the inner coma has allowed the 3-D reconstruction of Borrelly's gas and dust jets. Infrared spectra from MICAS allow estimation of the temperatures across the surface, while the PEPE instrument was able to capture detailed data about ion energies and densities in the comet environment.

DS1 has been, from start to finish, a remarkable project. Having convincingly demonstrated that ion propulsion and autonomous optical navigation are viable new tools for future planetary missions, the crippling loss of the SRU presented a daunting technical challenge. The DS1 team rose to that challenge. The pictures and science data successfully returned from comet Borrelly stand as a tribute to their determination and ingenuity.

ACKNOWLEDGMENTS

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